

Chapter 13

Procedures, Synchronization, and Automation

*It is only with the heart one can see rightly;
what is essential is invisible to the eye.*

—Antoine Saint-Exupéry, *The Little Prince*, chapter xxi

Around midnight on a stormy night, a medium-sized commercial jet was making its way into a midwestern airport. For the crew, this was the last flight in a four-day trip, with numerous takeoffs and landings, many hours of flying, and too little sleep.

“Turn left 150 degrees.”

“Roger, heading 150,” replied the captain to the air traffic controller’s instruction. The copilot was flying the aircraft. On this flight, it was his turn. A young man in his early 30s, the copilot was sitting close to the control wheel, holding it tight with his hands, trying to keep the wings level in the turbulent air.

They were gradually descending from 5,000 to 2,000 feet, and the captain was helping with the radios and procedures. He was also closely monitoring his copilot’s actions. The captain placed his hand on a small handle above the side window and pulled himself closer to the instrument panel. Passing 3,000 feet, he checked the instruments, compared the altitude in his altimeter to the altitude depicted on his copilot’s altimeter, and said, “One thousand feet to go.” He then rose up in his seat and peered outside. They were deep inside thick and heavy rain clouds, completely engulfed by darkness.

The plane was an older model aircraft, built in the late 1960s. There were just two pilots in the small cockpit. An aluminum-covered door was positioned behind them, and a large instrument panel—a myriad of dials, switches, and

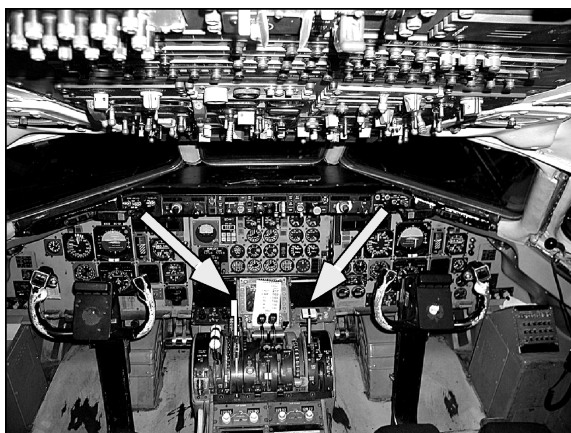


Figure 13.1. The cockpit (showing the two control wheels and the instrument panels). The throttles are located in the center of the pedestal between the two control wheels. The white arrow on the right points to the flap handle and the arrow on the left points to the spoiler level. Photo courtesy of Bevin Shively.

levers—in front (figure 13.1). On the right, the copilot was leaning forward toward the instrument panel, adjusting a switch. They were in a turn, descending toward an unseen runway that lay below.

As the aircraft continued its turn, the copilot looked at the captain and said, “Flaps extend, flaps five, please.” Between them stretched a long pedestal filled with levers, handles, and two small, sporty-looking throttles. The flap mechanism—which looks similar to a gear handle in an automatic car—was located by the copilot’s leg. The captain grabbed the flap handle, and pulled it back.

The sharp metallic sound of the flap handle moving toward the five-degree notch merged with the crackling voice of the air traffic controller that came through the speakers: “Turn left heading zero seven zero, maintain one thousand eight hundred feet until established on the approach, cleared for the approach.”

The controller was directing them toward the long runway that was hiding beyond the thick clouds. “Roger,” replied the captain. The copilot dialed 070 on his compass card and began the turn. Descending through the cloud deck, in the turn, they were blind to the outside—they could not see the horizon, nor could they see the runway. Only their instruments provided a clue as to their whereabouts. As the altimeter passed 2,000 feet, the copilot began pulling back on the control wheel, gradually leveling the aircraft at their assigned altitude of 1,800 feet. It was going to be yet another instrument approach to yet another wet and slippery runway.

“Flaps fifteen,” called the copilot.

The captain hesitated for a second, and then reached to grasp the flap handle with his right hand. A sudden gust from the left pushed the aircraft to the side. His hand hit the green metal pedestal between the two pilots and bounced back. He quickly retracted his hand and then came at the handle from above. Supporting his body on the glare shield with his left hand, he pushed the weight of his arm on the handle and firmly drove the flap handle down to the 15-degrees notch.

On the flap gauge, located just in front of the flap handle, a little needle plummeted down and settled close to the 15-degree mark. But the captain's eyes did not stay there for long. He quickly withdrew his gaze and moved it up the instrument panel toward his own instruments. Settling on a large display that showed the artificial horizon and a symbol of the aircraft wings (see figure 13.2), he straightway realized what had attracted his attention: on the left side of the display, a small diamond-like symbol was pulsating continuously. He coughed to clear his throat and then said: “Localizer alive.”

With the airport somewhere beneath the dark accumulation of clouds, the pilots relied on the instrument-landing system to help them fly toward the runway. At first, the horizontal (localizer) diamond was telling them that the runway was all the way to the left. But soon after, the little white diamond moved slowly toward the center of the display, indicating that the aircraft was progressively aligning itself with the center of the runway, 8 miles away and 1,800 feet below. The captain bent forward, glanced at the copilot for a second,

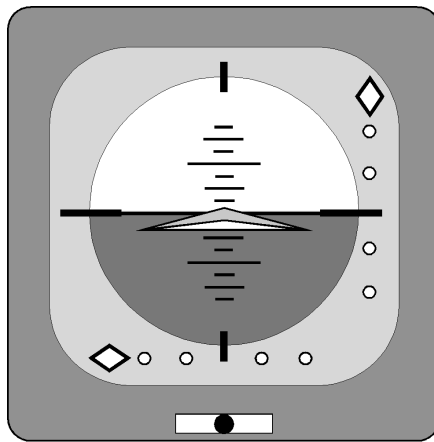


Figure 13.2. The artificial horizon display, showing the localizer diamond on the bottom (left) and the glide-slope diamond on the right side (top). Now the aircraft is below the glide-slope and the right of the runway.

took a quick glance at the instrument panel, and then started reciting the litany ingrained in him, one that had served him for hundreds of flights in this aircraft.

“We were cleared for the approach and the flight director is armed.” “Roger,” responded the copilot as he made a slight turn to further align the aircraft with the localizer diamond.

“Hydraulic pumps and pressure,” continued the captain, making sure that all pumps were on and their respective needles were in the green range. “Good,” he remarked quietly to himself as his eyes moved to inspect the other gauges on the instrument panel: the hydraulic-fluid quantity gauge indicated that enough pressure was stored to extend the gear and push out the flaps when necessary. Braking pressure was also in the green range. Everything here looked just fine, he thought to himself as the aircraft took another unexpected jolt. Seven miles out—and there was no end to the gusts.

Another little diamond appeared at the top-right side of the artificial-horizon display and began to shake. The captain welcomed it with a firm tone: “Glide-slope alive.”

“Gear down, Before Landing checklist,” came the immediate response from the copilot. The captain reached forward for the gear handle, pulled it out and then down in a quick, mechanized way. He kept his hand on the handle for a second or two, holding it in place, as if waiting for some response from the landing gear itself.

He did not have to wait long, because within two seconds a rumble sounded through the entire body of the aircraft—the large and heavy metallic doors housing the landing gear inside the aircraft opened into the icy air and disrupted the smooth flow of air under the aircraft. This was a normal response of the aircraft, expected, just like in any of the hundred landings that he had made in this aircraft, and the captain continued with the checklist by raising his arm to a large panel over his head. There, among a multitude of switches, buttons, and indicators, his hand reached for the engine ignition switch. He moved it from **OFF** to **OVERRIDE**, making sure that if the engine decided to quit during the descent to the runway, there would be plenty of ignition power to make a quick re-start.

The captain turned to his left and pulled a long, narrow piece of paper from his side—the checklist (see figure 13.3). Worn from use, its creases showing the signs of hundreds of not-so-clean fingers, the checklist looked like a restaurant menu. The captain gave it a quick look, and moved his gaze back to the instrument panel and his artificial-horizon display. The vertical (glide slope) diamond was sinking slowly toward the center of the display, the aircraft’s wings were level, and the copilot was also keeping the horizontal (localizer) diamond in the center. Assured that the aircraft was properly aligned with the runway, the captain lifted the checklist card closer to his face,

APPROACH CHECKLIST	
BEFORE LANDING	
IGNITION..... OVERRIDE
LANDING GEAR..... DOWN, THREE GREEN
SPOILERS..... ARMED
FLAPS..... EXTENDED, 40 DEGREES
ANNUNCIATOR PANEL..... CHECKED
AFTER LANDING	
SHUTDOWN CHECKLIST	

Figure 13.3. The aircraft checklist (showing only the BEFORE LANDING items).

adjusted the overhead light, focused his eyes on the small black letters that were bouncing with the never-ending turbulence, and began reading.

“Before Landing checklist:”

“Ignition,” the captain paused for a minute, looked up at the switch, and then announced—“Set to override.”

“Landing gear?”

He could hear the unmistakable noise and the constant vibrations indicating that the gear doors were wide open and the landing gear was sliding out of the aircraft’s belly. He looked down toward the triangle of three indicator lights just above the gear handle. The two outermost lights were shining bright green. Yet the center light was dark, indicating that the nose wheel was still coming down. Two seconds later the copilot called, “Gear down, three green.” The captain looked down again and confirmed that all three lights were shining green; the left, right, and front (nose) wheels were now fully extended and locked into place underneath the aircraft. Nevertheless, the landing gear was still not ready to touch the ground, because the gear doors that had opened to let the wheels drop out were slow to retract and fold back into the aircraft body.

The next item on the checklist was to arm the spoilers. The spoilers are large panels that pop up from the aircraft’s wing after touchdown and help stop the

airplane on the runway. The captain reached his hand forward to grab the spoiler lever and arm it—but he had to wait. There was a condition in the checklist telling him that he could not arm the spoilers until the gear doors were closed. And a small light above the gear handle indicated in bright amber that the doors were still open. He kept on looking at the amber light, thinking that within several seconds the doors would close, the amber light would turn dark, and he would continue with the checklist and arm the spoilers.

“Flaps 25,” said the copilot in a sharp voice.

The captain had to suspend the checklist to comply with his copilot’s request. Without losing a second, he reached forward and brought the flap handle down to the 25-degree notch. Meanwhile, the copilot was making small corrections with the wheel, focusing on the two diamonds that are part of the instrument-landing system. In conditions of poor visibility, like this night, the instrument-landing system, which sends a radio beacon from the runway up into the sky, was their trusted friend. The antennas in the aircraft received the radio signal, and the localizer and glide-slope diamond symbols indicated to the pilots where the beacon was. The copilot was keeping the localizer diamond in the center and waiting for the glide-slope diamond to come down toward the center of the display.

As the flaps were coming out, the aircraft’s speed slowed down to 175 knots, and the vertical glide-slope diamond was almost centered; a second later, it reached the center of the display. Now they were perfectly aligned with the beacon and the copilot did not hesitate for a second: “Glide-slope capture, flaps 40.” The captain responded immediately and moved the flap handle to 40 degrees. Sometime during these moments, the gear doors finally closed up and the small amber “gear door open” indicator went dark. But the captain was busy setting the flaps in response to the copilot’s requests; he was no longer looking at the gear lights. At the time, he couldn’t know just how many times later he would return to these seconds in his mind, wondering what went wrong and why he forgot to arm the spoilers.

With more flaps coming out and enlarging the surface area of the wing, the aircraft began to pitch down. The copilot pushed the steering wheel slightly forward, and the aircraft began to descend. The flaps were slowing the aircraft, and the copilot added some power on the engines. Flaps 40 was their final flap setting and also an item on the checklist (see figure 13.3). The captain gave the flap handle a jiggle, making sure it was secured in place. With his right hand still holding the flaps handle, he brought the checklist card up, refocused his eyes again on the black letters, looked at the copilot, and declared, “Flaps extend 40, flaps set, annunciator panel—to go.”

The small airspeed indicator read 160 knots. They were descending, riding down the invisible radio beacon toward the runway. The copilot stayed focused, constantly aligning the aircraft so that the two diamonds always

stayed centered. As long as he kept them centered in the display, they would continue to ride the beacon. And at the end of the beacon they would eventually find the runway. With the effects of wind and gusts, the aircraft might deviate from the beacon, but the display and the two diamonds were always there to tell the pilot how much to correct, either vertically or horizontally, in order to re-align with the radio beacon. The copilot corrected vertical deviations by adding or reducing power on the engines. As for horizontal deviations, although he could use the rudder pedals to make quick corrections, the copilot used the control wheel to turn the aircraft back toward the beacon.

The outside air was rushing toward them at 150 knots, but the wind was coming from the right. To keep the aircraft from deviating from its flight path, they were listing slightly on their right side, in kind of a constant right turn, sustained by the spread of the wings and the thickness of cold air. The altitude indicator showed 1,500 feet.

A loud chime sounded inside the cockpit!

Both pilots immediately looked up in surprise. “Disregard,” said the captain as he identified the source of the chime; the copilot’s body sank back in his seat and his eyes returned to the artificial-horizon display. The altitude alerter chime was simply warning them that they had deviated from their previously assigned altitude of 1,800 feet; they had forgotten to reset the altitude alerter when they began their descent toward the runway. The captain reached forward and reset the alerter to 200 feet. Finally, the gusts were subsiding. “One thousand feet above minimums,” said the captain. At that moment, a little light flickered in his peripheral vision. Above the dark window, on the overhead annunciator panel, the “rudder unrestricted” light was now shining blue, indicating that the rudder was available for use.

“Annunciator panel checked,” he affirmed, and then, lifting the checklist card, he announced: “Before landing check complete.”

They were coming down fast, but there was no sign of the runway; they were completely surrounded by a veil of clouds. The captain closely watched the altimeter and glanced at the engine gauges. He roused himself and said: “Seven hundred feet above minimums.” Since they could not see the ground, everything related to their altitude was referenced to “minimums.” The minimum altitude for this approach was 200 feet, which meant that if they could not see the runway when the aircraft altitude was at 200 feet, they would have to break off the approach, go around, and try again, perhaps at another airport.

One hundred and forty knots. The two diamonds were centered, which meant that they were tracking straight toward the runway and coming down the glide-slope perfectly—yet the captain looked around the cockpit with some apprehension. Something felt wrong. Something in this liturgy of actions, requests, checklists, and communications with air traffic control was

missing, but he just couldn't figure out what. Frustrated, he looked outside in anticipation of signs of terrain through the clouds. Nothing. Then he suddenly realized: the tower-approach control did not switch them to the tower frequency! They needed the tower's permission to land the aircraft.

He quickly keyed the microphone. "Approach control." "Approach," he said in a louder voice, "this is Flight 847."

"Approach, do you want us to go to tower?" The aircraft's speed was 137 knots. At least the copilot was doing a good job of keeping the speed on target and the aircraft on the glide-slope.

They were going to break out of the thick overcast soon, and he certainly did not want to meet the runway without a landing clearance. The captain grew a bit nervous as he called, "Five hundred feet above minimums," to the copilot, and continued with his efforts to hail the controller. "Approach, are you there?"

Still no radio contact.

The captain tried to figure out if the microphone's jack was out of the socket or maybe something else was malfunctioning. As he was about to push the microphone switch for another attempt, a soft and sleepy voice entered the cockpit: "Sorry, contact tower on frequency 128.2." He hastily ratcheted the new frequency into the radio and immediately pushed the microphone's talk button: "Tower, this is Flight 847, we are with you on the approach, ILS runway zero four."

"Cleared to land," came the immediate response.

The captain, relieved, made a quick scan of the cockpit instruments: 400 feet above minimums, 1.7 miles out, 137 knots. The instrument landing system (ILS) was working just fine and they were tracking it in—now they were a bit above the glide-slope and the copilot was making a correction to close in. He quickly moved his eyes above the instrument panel and into the gloom beyond the window, and caught a glow of light. "Three hundred above minimums." Ahead and below, through the dark gray clouds, he could now see a misty pink light bouncing forward. Then the pink became red. And a string of bouncing red lights lay ahead.

He focused on the red lights and his eyes followed them as if pulled forward by some invisible string. The clouds opened up and he saw the runway's lights.

"Runway in sight."

"Going visual," came the quick response from the copilot as he raised his head. The runway scene was coming alive—the set of red lights shining ahead marked the beginning of the runway, with white lights bordering the runway on both sides, and soft blue taxiway lights fading beyond. The runway's center line greeted them with its dotted white lights. The copilot focused on the centerline lights, aligning his body and spine with them. A little bank to the

right, a quick push on the rudder pedal, and now the aircraft was in line with the runway.

"In the groove," said the copilot in a satisfied tone. The captain made a final check inside the cockpit to make sure that everything was set properly for landing. All the landing gear lights were shining in green, "good"; the flaps handle was in the 40-degree notch, "check"; and engine thrust was "okay." But something was out of place; he could almost feel it in his body. Noting the copilot's hands tightening on the throttles, knowing the plane would be landing in a few seconds, the captain made another scan up and down the pedestal for evidence of any problem. Then he saw it. There, by his right leg, the spoiler lever was down; the spoilers were not armed and ready for automatic deployment.

"Missed it on the checklist," he muttered to himself with a sharp resentfulness. He hurriedly reached his hand forward to grab the lever and arm the spoilers. And then he hesitated.

Years of experience told him that this was not the right thing to do. His muscles and sinews held his hand back from arming the spoilers at this altitude. They were only 300 feet above the runway. Changing the aircraft's configuration at this low altitude was dangerous; any fault in the automatic spoiler system could result in automatic deployment of the spoilers in mid-air and cause the aircraft to sink precipitously. Arming the automatic spoilers now was not a good idea. No way around it, he thought to himself; he would have to manually deploy the spoilers once they touched the runway.

"Two hundred feet to touch-down," called the captain, and then he silently said to himself, "And when we touch down, I reach for the lever, pull it up, back, and then up again." This was his mental preparation for manually deploying the spoilers once they touched the runway.

"One hundred feet."

The copilot pitched up the aircraft slightly for landing. There was a slight updraft at the same moment, the aircraft wallowed upward, and the copilot's left hand slowly moved the throttles backward. A second later the engines were whining down. The airplane, about to land, was in a vulnerable state—pitching up, slow, and very close to the ground. A gust from the right lifted the wing, and the copilot quickly corrected with a quick turn of the wheel to the right. They were slow, almost hanging in the air. The wings leveled and their eyes were glued to the runway-center lights. The captain's hand moved to the spoiler lever. The black runway widened and his hand closed around the lever. As the runway lights rushed up toward them, his right hand clutched the spoiler lever hard. An updraft from the left jolted them and the entire aircraft vibrated in response. The copilot corrected to the left and pushed the throttles to the very end—"clack," came the metallic sound of the throttles hitting the

hard backstop. “Reach, pull it up, back, and then up again,” the captain said to himself as his hand pulled back on the spoiler lever.

The bottom suddenly dropped out from beneath them.

The aircraft was no longer flying. It sank like a brick. The copilot instinctively pulled back on the control wheel to stop the aircraft from sinking further. But this corrective action was futile, because within a second the aircraft’s tail hit the ground with a thud.

“Damn,” said the captain as the entire hull shuddered. The left wheels took much of the impact, then the right wheels shortly thereafter. The sound of aching metal echoed from the tail of the aircraft through the cabin and then up to the cockpit. They felt the violent and jarring shock in their tailbones, up their spines, through their ribs, chests, and necks, all the way to their heads and eyes. The landing gear produced hollow guttural sounds as the hull’s frame and bulkheads responded with pain. It seemed that every piece of metal wobbled and every rivet in the aircraft shrieked. Then the nose wheel came down hard on the black pavement, bouncing them in their seats.

The copilot pushed anxiously on the brake pedals to stop the aircraft. The captain grabbed two small levers on the throttles and pulled them back; the engines reversed and slowed down the aircraft.

“80 knots,” the captain’s voice rang out.

“I have control,” said the captain as he took the aircraft in his hands; and with those three simple words he took upon himself the emotional weight of the impact and relieved much of the copilot’s anxiety.

They slowed to a walking pace midway down the runway, and from there throttled the aircraft into the next taxiway. Now everything was silent, but their bodies were still reverberating with the shock. The captain understood what had happened and was quick to realize the consequences of this incident for him. He apologized to the copilot, and with a heavy heart picked up the checklist card from his side and began:

“After landing checklist;

“Lights—nose lights dim.”

“Flaps—15.”

“Antiskid—off.”

Later the next morning, the mechanics checked the aircraft thoroughly. There was serious damage to the tail, which hit the runway before the wheels. The impact registered almost 1.5 times the weight of the aircraft. Support structures and metal frames in the tail section sustained imploding damage. Some rivets had popped out. The skin of the aircraft around the tail was wrinkled and scratched. One of the supporting belts that connects the landing gear to the airplane was broken. The landing gear, which absorbed most of the impact, was bent in agony. The center fuel tank, lying close above the tarmac, had sprung a slow and weeping leak.

What Went Wrong?

The captain's premature deployment of the spoilers while the aircraft was about 20 feet above the ground caused the hard landing. It looks like another one of those "human error" stories we read about so often in the newspapers. The captain was the definite culprit: first, he forgot to arm the automatic spoilers. Second, he failed to follow the checklist sequence and skipped over the "spoiler arm" item. Third, when he finally realized the omission, he manually deployed the spoilers at the wrong time.

"Pilot error." Case closed!

But as we have seen in the preceding chapters, human-machine interactions, especially in highly dynamic environments, are far from simple. To truly understand what happened, we first need to look carefully at the automatic spoiler system, the procedure to operate it, and the checklist. Only then can we truly judge what really happened.

From Air to Ground

Landing an aircraft is a delicate and complicated maneuver. The aircraft, flying at speeds in excess of 150 miles per hour, must be guided from the wide-open sky to a narrow strip of runway and then brought to a stop. In flight, the aircraft's weight is supported by the air; once on the runway, the landing gear takes the load. The transition from flying to rolling down the runway is a gradual process, because, even after the wheels touch the ground, there is still air flowing beneath the wings, supporting the weight of the aircraft. Prolonging this gradual process is something to avoid, or, more precisely, to minimize. Why? Because the longer this transfer of weight takes, the longer the aircraft will roll on the runway before finally stopping. Runways are limited in length. And when there is rain, snow, and slush, they effectively become even shorter.

And this is where the spoilers come into the picture: they pop up at touchdown to help the aircraft settle firmly on the ground. The spoilers, as the name suggests, spoil and disrupt the flow of air over the wings and thereby reduce lift. You may have seen them on the aircraft's wing during landing: big wide panels, several feet long, which rise up from the wing's surface immediately after touchdown and stay up until the aircraft slows down.

Once the aircraft is firmly on the ground, the pilots stop the aircraft by pressing on the brake pedals, just as you do in your car. When the airplane's weight is mostly on the landing gear, the brakes are more effective. This allows for a short and quick landing. Efficient braking is even more critical while landing on a wet and slippery runway, because, just like in your car, if the asphalt is wet it will take longer for braking action to be effective. It is therefore critical to make sure the spoilers are deployed to help the aircraft settle firmly

on the runway. Aerodynamic calculations show that if the spoilers are not deployed after touchdown, the wings support about 70 percent of the aircraft's weight, and only 30 percent is carried on the landing gear. However, if the spoilers are properly deployed, 80 percent of the weight is quickly transferred to the landing gear. When most of the aircraft's weight is on the landing gear, the aircraft will stop faster. Spoilers, as you can see, make a huge difference in efficient braking. Forgetting to arm the spoilers and/or improper deployment of spoilers has caused many aircraft to slide on the runway, including several accidents in which the aircraft overran the end of the runway (see the notes for this chapter).

The Automatic Spoiler System

Having considered the function of ground spoilers, we can now focus on how they work and how the pilots operate this system. The spoilers can be deployed manually or automatically. As soon as the aircraft touches down, the pilot can manually pull the spoiler lever and deploy the spoilers. Just like a handbrake in a car, the more the pilot pulls the spoiler lever toward him or her, the more spoilers come out of the wing to disrupt the airflow. That's the manual option.

The other option is to have the spoilers pop up automatically during touchdown. There are two advantages to automating spoiler deployment: one, having the spoilers pop out just at the right time, not too early and not too late, provides for maximum braking efficiency (and perfect timing is something that a machine is well-suited to do); two, automatic deployment reduces the pilot's workload, which, as we have seen, is quite high and challenging during landing. So this is not a bad idea, but how does the aircraft know when to deploy the spoilers? We want to be assured that the spoilers will come out only when the aircraft is on the ground (and not in the air). Inadvertent deployment of spoilers in mid-air will cause the aircraft to sink rapidly—a situation that can easily deteriorate to a stall condition in which the aircraft's wing can no longer produce lift and the aircraft falls out of the sky.

Since it's important that the spoilers deploy as soon as the aircraft's wheels touch the ground, there is a sensor on the nose wheel for this. When the sensor is activated, an electric pulse is sent to the aircraft's logic circuits signaling contact with the ground. This triggers the spoiler mechanism to automatically deploy the spoilers. Because the spoilers are so critical for landing, there is a built-in redundancy so that another event can also trigger the spoiler mechanism (in case the nose wheel sensor fails). The sensor for this event is located on the main wheels; it sends an electric pulse when the wheels are spinning (as opposed to skidding). Specifically, the sensor will send the pulse when the wheels are spinning at an RPM that's equivalent to 80 knots. Therefore, either one of these two conditions,

nose wheel sensor = GROUND
 or
 main wheels' speed = 80 knots

will automatically deploy the spoilers.

Figure 13.4 is a model of the automatic spoiler system. It describes the system and the pilot's interaction with it. The system starts in state *A* with the landing gear up. Then the spoiler is armed (state *B*) and the landing gear comes out (state *C*). It takes some time for the landing gear to come out of the aircraft's belly, unfold, and lock into place. Once the gear is down and locked in place, there is a transition to state *G*—the gear is down and the spoilers are armed. When the aircraft touches down, the spoilers pop out automatically (state *H*), and everything is well.

But things do not always go as planned. It turns out that the above sequence (*A-B-C-G-H*) has some potential hazards. Years of operational experience with this aircraft has shown that state *C* is dangerous because of the mechanics of the landing gear and the sensor that signals “GROUND.” This sensor is located inside the nose-wheel strut, which is similar to the shock absorbers on cars and on mountain bikes. When the strut compresses to less than three inches, the sensor signals that the aircraft has touched the ground. But there is a real possibility that the strut will also compress to less than three inches when the nose wheel slides out of the aircraft's belly and is greeted by extensive pressure from the rush of the air around it. When this happens, the strut may compress to a point that the GROUND sensor activates, and the spoilers will deploy while the aircraft is in mid-air. The consequences are potentially serious: the aircraft will sink fast and may even stall (see endnotes).

A Disturbance Event

Having the ground spoilers pop out unexpectedly in mid-air is not a welcome prospect, because it can lead to a catastrophe. State *D* in figure 13.4 denotes an unexpected spoiler deployment in mid-air. Reaching this state, which is always a possibility, is *unsafe* and we certainly want to prevent it from happening. But how do we do this?

Let's first try to consider how we may inadvertently find ourselves in this unsafe state where the spoilers pop out in mid-air. We get to this unsafe state only when the *errant* GROUND signal event takes place in *C*. Note that this type of event is different from all the ones we encountered in previous chapters: it is not *manual*—the user did not trigger it—and it is not *automatic*, because it is not a timed event or an internally computed event (like ones we have dealt with in the clock radio and the autopilot of KAL 007). So what is it? The dotted transition in figure 13.4 is a *disturbance*, an event that is triggered by the environment or by some fault in the system.

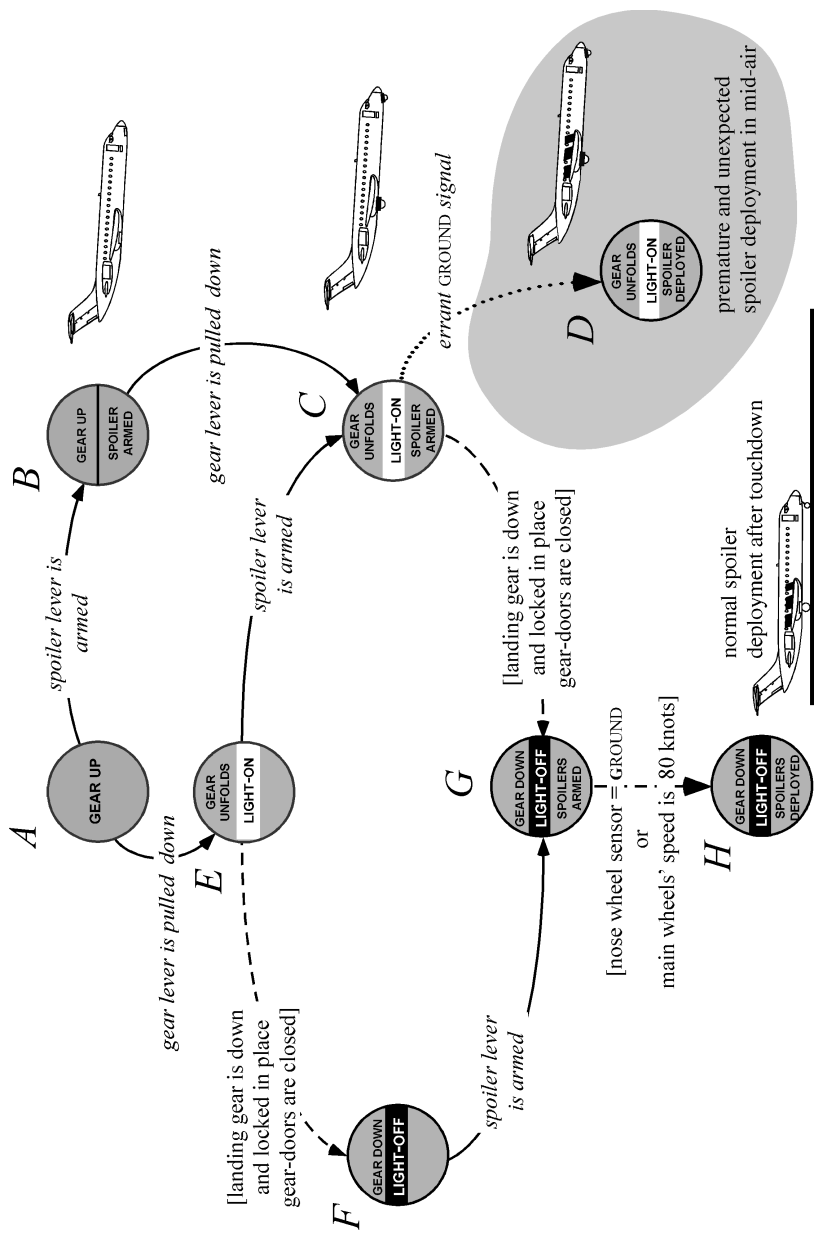


Figure 1.3.4. Machine model of the automatic spoiler system.

The occurrence of a disturbance is always unpredictable. We do not know when it will happen (and we do not really care, for the purpose of this analysis, if it will happen once in every 10 flights or once in every 1,000 flights). All we know is that it *may* happen and it is dangerous. We therefore want to block it from happening, and the sure way to do this is to avoid reaching configuration *C*. That is, we should avoid altogether arming the spoilers before lowering the gear. But note what we just did: we are restricting entry into configuration *C*, which by itself is not dangerous, only because it harbors the *potential* for a disturbance event. For all practical purposes, state *C* is also *unsafe* for us.

So how can we avoid state *C* and still lower the gear and arm the spoilers? Let us look again at figure 13.4. One way to avoid these two unsafe states (*C* and *D*) is to use another path. Consider the following sequence: Lower the gear (and transition to state *E*), wait for the landing gear to fully come down and lock into place (state *F*). But how do we know when the gear is down and locked in place, and that it is therefore safe to arm the spoilers?

Recall that there is an indicator light in the cockpit to announce when the gear extension sequence has been completed. It takes the landing gear system somewhere between 17 and 39 seconds to come out, unfold, lock into place, and then for the gear doors to close. During this period, a little amber light, “gear door open,” which is located by the gear handle, illuminates. When the landing gear locks in place, ready for landing, and the gear doors finally close, the light goes off. Only then should the pilot arm the spoilers (and transition to state *G*).

The new sequence, *A-E-F-G*, guides the pilot through lowering the gear and arming the spoilers and guarantees that we will never enter the unsafe state *D*. In other words, to avoid inadvertent spoiler extension in mid-air, the pilots must follow a specified sequence of actions.

Such a sequence is called a procedure.

Procedures

A procedure specifies a unique sequence of actions; it is a recipe of sorts. It shows us the necessary steps to perform a task, such as arming the spoilers for landing. Figure 13.5 is a description of the spoiler arming procedures. The procedure also tells us when to begin and end the sequence of action. We begin the procedure by lowering the landing gear, and we terminate it after the spoilers are safely armed, the gear is down, and the gear doors are locked in place. Procedures, however, are not limited to aircraft operations—you find them almost everywhere you see a human interact with a device, and especially if it is done in a risky environment.

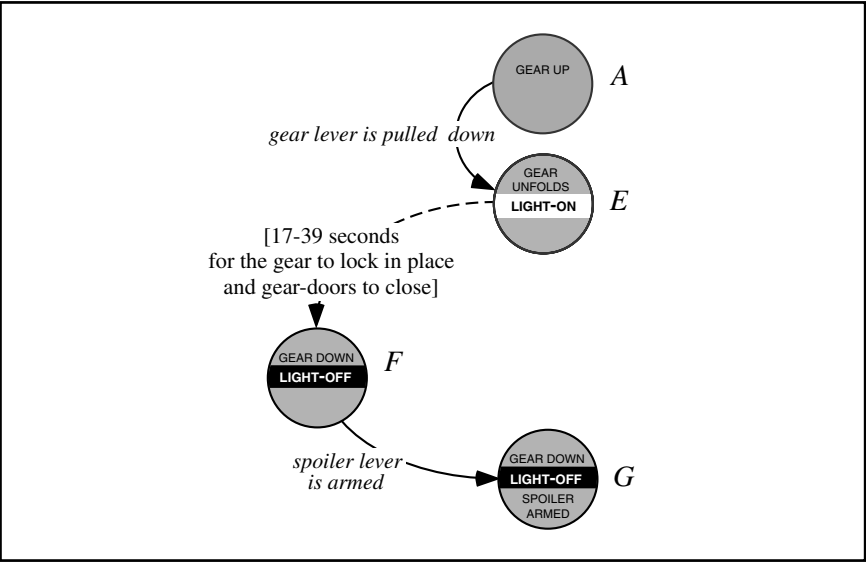


Figure 13.5. Spoiler arming procedure.

Sometimes the sole reason for a procedure is an inherent problem in the design of the system. This is the case with the spoiler deployment procedure here. In the case of the blood-pressure machine (chapter 12), it is possible to specify a mandatory sequence of actions for changing the timer interval. Using procedures and instructions to bypass an unsafe state may appear, on the surface, to be a perfectly cheap and easy solution. Simply write a procedure, print it on a placard, place it by the device—problem solved. But mandating a procedure in lieu of making a design or interface change is really only putting a Band-Aid on the problem. Why? Because the underlying assumption is that the user will *always* follow the procedure. Yet humans, like it or not, are not machines. Either advertently or inadvertently, at one time or another, a procedure may go unused. And if you think it is always possible to make sure that a procedure is followed, just think about all the safety procedures and instructions that you have violated while using power tools and installing electrical devices at home. There is never a full assurance that procedures will be followed, no matter how many are specified.

Nevertheless, not all procedures are Band-Aids for design deficiencies. Some procedures are in place to provide guidance to the user on how to work the machine. In order to operate a complex system successfully, the user must be well supported by procedures. In high-risk systems, such as aircraft operations, space flight, nuclear power, chemical production, and high-technology medical practices, it is essential that such support be flawless—as the price of errors can be high. Therefore, first and foremost, a procedure must

be correct in the sense that it must not lead the user into unsafe states as well as situations from which the user cannot recover.

Instrument-landing Procedure

Flying a commercial aircraft involves many complex and critical tasks. To make sure that these tasks are performed safely and to maintain a high level of safety on every flight, airlines mandate procedures. The intent is to provide guidance to the pilots and to ensure logical, efficient, and predictable means of carrying out tasks. Procedures are also in place so that each crew member will know exactly what each other crew member is doing, and what action he or she will take next.

An instrument approach for landing is a highly complicated task, and indeed all airlines provide their pilots with a specific procedure for performing it. The procedure tells the pilot what to do and provides cues for when to do it. Figure 13.6 is a description of the sequence of actions that were part of the instrument landing procedure used during the accident flight. There are three steps that we focus on:

1. The gear should be lowered as the aircraft starts to receive the glide-slope signal;
2. Flaps should be set to 25 degrees as the aircraft nears the glide-slope.
3. Flaps should be set to 40 degrees as the aircraft captures the glide-slope.

The timely execution of this procedure depends on the aircraft's speed. It is possible to calculate the time it takes the aircraft to fly from one point to the other. Below the instrument approach profile in figure 13.6 is a timeline: For an approach speed of 175 knots, it takes 10 seconds to fly from point 1 (gear down) to point 2 (flaps 25). It takes the aircraft an additional 6 seconds to get from point 2 to point 3 (flaps 40). Altogether, it takes 16 seconds to fly from point 1 to point 3.

Synchronization of Procedures

Hardly any aircraft procedure is conducted in isolation. Many procedures are executed concurrently. In our case, both the spoiler extension procedure and the instrument landing procedure run concurrently. The question now is whether they are well synchronized, so that one procedure sequence does not block or disrupts the other's sequence (and vice versa).

Naturally, the difficulty of evaluating such concurrent procedures increases when there are three, four, and perhaps more procedures running at the same time. Multiple (and concurrent) procedures are the reality in aircraft opera-

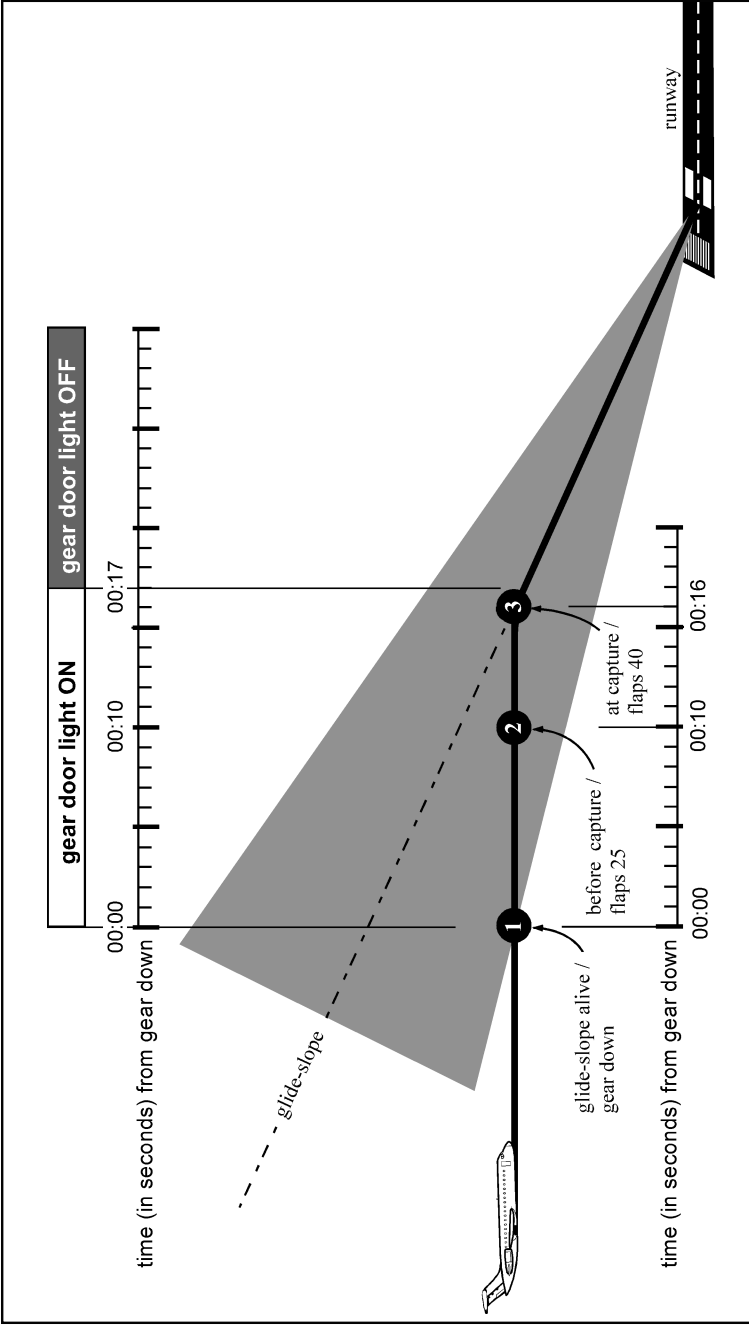


Figure 13.6. Instrument-landing approach procedure (not to scale).

tions and other safety-critical systems. Moreover, having well-synchronized procedures becomes even more critical during high-tempo phases of a flight, such as during an instrument approach for landing.

Synchronization is all about timing. Recall that both the spoiler extension procedure and the instrument-landing procedure start with lowering the landing gear. That is the initial event for both procedures. The spoiler extension procedure tells the pilot that he must wait for the gear door light to turn off before arming the spoilers (and we know that from gear-down it takes at least 17 seconds for the light to extinguish). The instrument-landing procedure tells the pilot to set flaps 25 and then flaps 40 (and we already know that from gear-down it takes 16 seconds to reach flaps 40). At the top of figure 13.6 you can see the timeline for arming the spoilers; at the bottom of the figure is the timeline for flying the approach and setting the flaps. Looking at figure 13.6, we note that flaps 40 (point 3) will always occur *before* the gear light turns off. Therefore, spoiler arming can be initiated *only* after flaps 40. Does this limitation have any relevance here?

Checklist

Let's turn to the checklist to find out. The pilot's tasks in preparing and checking that the aircraft is ready for landing are listed in chronological order on the **BEFORE LANDING** checklist (which, of course, is yet another procedure). The checklist is in place so that the pilot won't forget or skip items and fail to prepare the aircraft for landing. The pilot must follow the checklist item by item, making sure that all actions have been accomplished. Figure 13.7(a) is the **BEFORE LANDING** checklist sequence. It tells the pilot to:

1. lower the gear, then
2. arm the spoilers, and only then
3. check that the flaps are set at 40 degrees.

But when we take into account the time it takes to accomplish items (2) and (3) we find a sequential problem. It takes at least 17 seconds (from gear-down) until the pilot can arm the spoilers; yet it takes 16 seconds (from gear-down) to reach the flaps 40 point. Therefore, flaps 40 (item 3) will occur before the pilot can arm the spoilers (item 2). See the problem? The checklist's mandated sequence 1-2-3 can be performed only as 1-3-2 given the actual dynamics of the aircraft.

Thus, in the accident described above, the captain had to wait for the gear door light to turn off before he could arm the spoilers. But in the meantime, the airplane was moving and the copilot instructed him to set flaps 25, and, shortly after, flaps 40. Flaps 40, as shown in figure 13.7(a), is a checklist item. So what

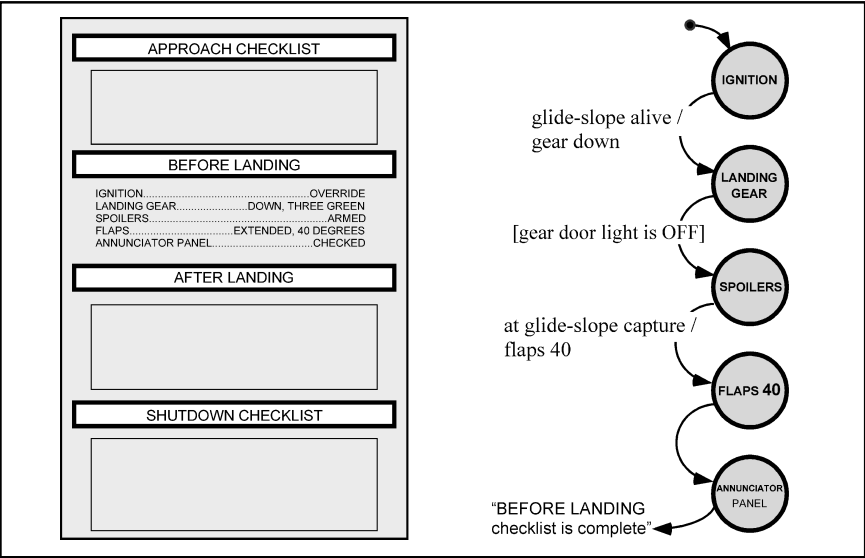


Figure 13.7 (a). The BEFORE LANDING checklist card and sequence.

does he do after moving the flap lever to 40? He calls “Flaps 40 set,” picks up the checklist and continues on—completely bypassing the spoiler item!

Notice what unfolded here: the specified and mandated sequence of “gear-spoilers-flaps 40” got switched with the truncated sequence of “gear-flaps 40.” You can see this visually in figure 13.7(b). As a consequence, the spoiler check was out of the picture, and the pilot forgot to arm them.

Possible Solutions

How do we go about solving this procedure synchronization problem? One possible solution is to modify the BEFORE LANDING procedure sequence to account for the fact that “flaps 40” can come before “arming spoilers.” This seems to be a simple fix. However, we must be very careful here, because such fixes must first be evaluated in the context of all procedures.

A better (and much safer) solution is to redesign and modify the landing-gear mechanism and/or the spoiler deployment logic with the intent of eliminating the possibility of inadvertent spoiler deployment. This way, the spoiler can be armed anytime and there is no need for the doors to close before the pilot can arm the spoilers. Nevertheless, such modifications can be rather costly, especially when applied to dozens of aircraft. So it is not surprising that although the manufacturer of this aircraft sells a modification kit for the spoiler/landing gear mechanism, no U.S. airline has yet bought it.

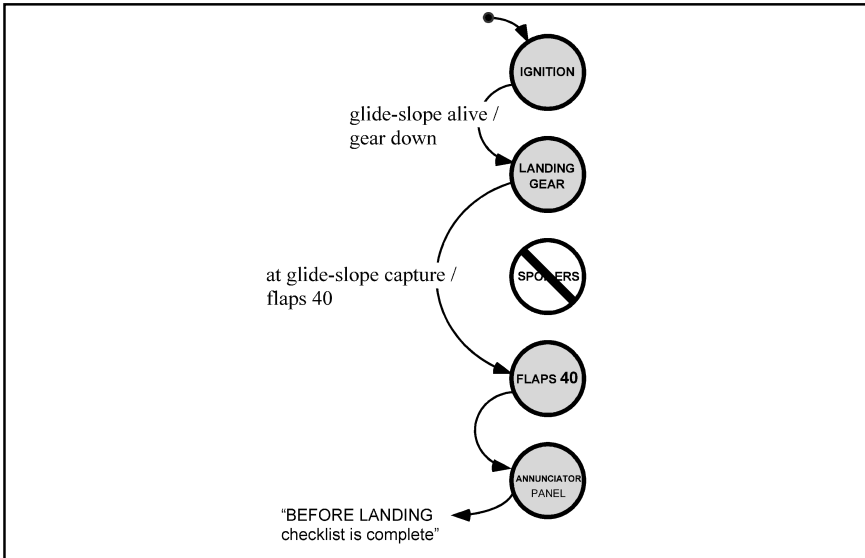


Figure 13.7 (b). The actual sequence during the flight.

Regardless of which of the above solutions is adopted, there always exists a possibility that the pilot will forget to arm the spoilers for landing. In the current design, there is very little feedback to the pilot that the spoilers are not armed and ready for landing. And since forgetting to arm the spoilers is a known problem that has contributed to many incidents and accidents, it may be also beneficial to install an indicator (or another design feature) that can sense when the spoilers are not armed and warn the pilot.

The Effect of Priming

The above discussion showed the synchronization problem and we now appreciate why the arming of the spoilers was skipped over and missed on the checklist. We have also seen that checklists, being a temporal list of actions and checks, are extremely vulnerable to omissions and timing constraints. Once an item is skipped over, there is often no return because the user assumes that all is well and moves on. In this accident, reaching the end of the checklist gave the captain a false assurance that the list was complete. But the captain noticed, just before the landing, that he forgot to arm the spoilers; he then pulled the spoilers manually, but at the wrong time.

Why?

This question is difficult to address because now we are in the not-so-exact realm of human performance. We know, however, that before the captain

manually pulled the spoilers, he rehearsed the action sequence verbally to himself: “And when we touch down, I reach for the lever, pull it up, back, and then up again.” In a way, he primed himself to pull the spoilers. Such priming is something that we have all encountered and seen before. We see it sometimes in the Olympics, when swimmers are ready to jump off the starting blocks at the sound of the gun. Someone in the audience claps, or some noise is heard—and then one swimmer jumps off to a false start.

Competitive swimmers prime themselves so that the sound of the gun triggers a jump. A similar sound or a related cue causes them to jump. Considering that the captain primed himself to manually deploy the spoilers, something must have triggered his action. What was the event that triggered him to assume that the aircraft was on the ground and then pull the spoilers? Did he mistake a movement of the aircraft, due to a downdraft, for a landing? Did the metallic clack of the throttle, as it was pulled back, provide an auditory trigger? Was fatigue an additional factor? The sad truth is that it is very difficult to answer these questions with any sense of precision and confidence.

In Conclusion

In this chapter we evaluated the correctness of a single procedure (arming spoilers), then added a concurrent procedure (instrument landing), the checklist, and finally added time as a factor. We saw how synchronization among sequences of action and timing constraints play an important role in the design of procedures. The objective of this chapter was to show how subtle timing inconsistencies can cause a critical human-machine interaction to fail and then to demonstrate a general approach for evaluating and designing procedures that are correct.

Correctness of procedures is an important aspect of human-machine interaction and becomes even more important in human interaction with automated systems. The reason is not only that the human is a player in executing procedure steps, but that the machine can trigger events automatically. Furthermore, as we have seen in the spoiler-arming example, the environment can also play a role and create disturbances that may drive the system into an unsafe state—sometimes with detrimental results.

Beyond procedures, we also came to realize that an accident like the one described in this chapter is a complex sequence of events that come together in some unexpected way. It is impossible to completely eliminate accidents. However, it is possible to reduce their likelihood by removing much of the “fuel from the fire.” Forgetting to arm the spoilers during an approach is hardly a new problem; it has happened to many pilots. Sometimes the pilots catch the omission; sometimes they do not. Interestingly enough, many pilots who have

encountered this particular timing problem and skipped over arming the spoilers believe that it occurred because they were not attentive enough, failed to follow the checklist, or they attribute the omission to a similar “guilt trip.” The reality, as we now know, is more complex.

It is important to note that we all have a tendency to fixate on one major flaw as the explanation for an accident: In this case, some may blame the pilot for pulling the spoiler at the wrong time, others will blame the design of the spoiler mechanism, or blame the way the procedure is written. But the naked truth is that most accidents lie in the interaction of many factors. These factors are technically complex, involve human performance issues that are not well understood and predicted, and are intricate in the sense that there are several concurrent processes going on at the same time. What makes it especially difficult to describe and fully understand many problems associated with the correctness of procedures is the delicate synchronization requirements and timing constraints that are invisible to the eye. Nevertheless, these requirements and constraints are essential for developing correct procedures for automated control systems.

Chapter 12

The incident described in this chapter took place several years ago at a large teaching hospital. The incident is detailed in a chapter, titled “Automation in anesthesiology,” by David Gaba, M.D. which appeared in a book titled *Human Performance in Automated Systems: Current Research and Trends* by Mustapha Mouloua and Raja Parasuraman (Erlbaum, 1994, pages 57-63). The incident was not an isolated case, similar incidents have occurred in the past and the problem is known to many anesthesiologists. After the incident was investigated, the hospital management decided to remove this particular model of blood-pressure machine from all surgeries and wards.

In writing this chapter, I have relied on several academic publications on the topic of human factors in medicine. The book *Human Error in Medicine* (edited by Marilyn Bogner and published by Erlbaum, 1994) provided background information, as well as *Under the Mask: A Guide for Feeling Secure and Comfortable During Anesthesia and Surgery* by Dr. James Cottrell and Stephanie Golden (Rutgers University Press, 2001).

Chapter 13

The aircraft accident described in this chapter occurred several years ago. The factual information is based on the cockpit voice recorder and flight data recorder. The non-factual description and the painting of the scenes are based on my own flying experience. The actual evaluation of this procedure and the synchronization problem is somewhat more complicated than presented here, yet the results are the same. In writing this chapter I drew on previously published work conducted with my former advisor, Professor Earl Wiener, on the use and design of procedures. (See Asaf Degani and Earl Wiener, *The Human Factors of Flight-Deck Checklists: The Normal Checklist*, NASA Contractor Report number 177549, published in 1990; and *On the Design of Flight-Deck Procedures*, NASA Contractor Report number 177642, 1994.)

Problems in arming spoilers for landing have occurred in the past and contributed to many incidents and to a few accidents: In 1999, an American Airlines MD-80 aircraft crashed while landing on a wet and slippery runway in Little Rock, Arkansas. The American Airlines pilots also forgot to arm the spoilers before landing. Once they landed, as much as they tried, they were unable to stop the aircraft before the end of the runway. The aircraft overran the runway and broke in half, killing the captain and ten of his passengers. The full report on the American Airlines Flight 1420 accident can be obtained from the National Transportation Safety Board (NTSB) or downloaded from their web site (*American Airlines Flight 1420, Runway Overrun During Landing, Little Rock, Arkansas, June 1, 1999*; NTSB report number AAR-01/02).

Premature deployment of spoilers has also occurred in the past. On July 5, 1970, a McDonnell Douglas DC-8-63, operated by Air Canada, was making an approach to Toronto-Pearson International Airport. Sixty feet above the runway, the aircraft all of a sudden began to sink rapidly. The right outboard engine was torn off the aircraft in the subsequent heavy landing. The crew initiated a go-around and climbed to 3,000 feet. Then, a large piece of the right wing separated from the aircraft. The DC-8 stalled and crashed, killing all 109 people on board. The investigation report declared that the probable cause of the rapid descent while the aircraft was close to the runway was premature deployment of spoilers. As a result of this accident, the U.S. Federal Aviation Administration issued an Airworthiness Directive cautioning pilots against in-flight operation of ground spoilers by

requiring the installation of a warning placard in the cockpit and the insertion of an operating limitation in the aircraft's flight manual cautioning pilots not to use ground-spoilers in flight.

The general topic of procedure correctness is rather involved and beyond the scope of this book. But generally speaking, a procedure is a (conditional) sequence of actions aimed at driving a system safely from an initial state (e.g., lowering the gear) to a desired end state (e.g., gear is locked in place and spoilers are armed). Since the user's actions frequently interact with the system's and the environment's responses, the user's actions are conditional on these responses. To this end, one requirement of a correct procedure is that there will be no known situations in which an automatic event or a disturbance will unexpectedly drive the system to an unsafe state (e.g., as in the case of premature spoiler deployment in mid-air). For an additional example and discussion of correct procedures, see Asaf Degani, Michael Heymann, and Michael Shafto, "Formal Aspects of Procedures: The Problem of Sequential Correctness," a short paper that appeared in the 1999 *Proceedings of the 43rd Annual Meeting of the Human Factors and Ergonomics Society*.

When timing constraints are involved in the procedure's execution, the correctness of a procedure is more subtle, because a specified sequence of actions might become unattainable—thereby disrupting the sequence (and possibly forcing the user to skip over an essential operation). It is also important to note that when executing a procedure that involves a dynamical system, the user and the system are in a race against time, an issue that becomes paramount when considering emergency procedures such as in-flight fires.

Finally, just like in interface design, making sure that the procedure is correct and safe is only the first step. For the procedure to be correct and also useful and suitable for the user, the procedure must be further refined. Consideration must be taken so that the procedure steps are clear to the user. Namely, that the user actions prescribed in the procedure leave no room for ambiguity. Likewise, that information such as values and state of the system are easily obtainable from the interface and are not subject to interpretation. Additional considerations are about the relationship between the sequence of the procedure and the layout of a control panel, how the procedure fosters coordination in a multi-person crew, and how the status of the procedure (awaiting a response, completed, needs to be executed again) is shared among the crew members.

Chapter 14

This year, 2003, marks the centennial of powered flight. On December 17, 1903, after many unsuccessful trials, Wilbur and Orville Wright made a series of engine-powered flights and realized one of humanity's greatest dreams—to fly. The famous picture showing Orville flying several feet above the ground, and Wilbur running in chase, have us all suspended between our primal connection to the earth and our desire to reach for the stars.

The aircraft speeding incident described in the chapter took place several years ago. I took the liberty of simplifying some of the details regarding the autopilot and flight management computer, so as to make it more understandable and readable. The full details exist in my Ph.D. dissertation, *Modeling Human-Machine Systems: On Modes, Error, and Patterns of Interaction* (Georgia Institute of Technology, Atlanta, 1996) and in an article titled "Modes in Human-Machine Systems: Review, Classification, and Application," by Asaf Degani, Michael Shafto, and Alex Kirlik, which was published in 1999 in the *International Journal of Aviation Psychology* (volume 9, issue 2, pages 125-138).